Creating a multifunctional composite stator slot material system to enable high power density electric machines for electrified aircraft applications

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AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), July 12-13
Cincinnati, Ohio
Electric Machine Motivation: STARC-ABL

Conventional tube and wing design along with minimal battery dependence makes this a near term possibility (2030ish)

Electrical Machines
- Two 1.4 MW generators mounted near turbines
- One 2.6 MW motor driving tail cone thruster

Geared Turbofan
- HP Spool = ? rpm
- LP Spool = 6800 rpm (generator connects here)

Tailcone Thruster
- Fan = 2514 rpm
- Diameter = 80.2"
- Hub/Tip Ratio = 0.3
- Hub Diameter = 24.1"

UTRC Concept for HGEP Thermal Management

High Power Density Electric Machine

UTRC concept for Hybrid Geared Turbofan

Max Temp
<table>
<thead>
<tr>
<th>Cooling Loop</th>
<th>°C</th>
<th>°F</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant</td>
<td>60</td>
<td>140</td>
<td>333</td>
</tr>
<tr>
<td>Oil</td>
<td>135</td>
<td>275</td>
<td>408</td>
</tr>
</tbody>
</table>
Electric Machine Motivation: NASA Efforts

- Internal NASA motor development
  - Target >98% Efficiency Stretch Goal 99%
  - 16 kW/kg
  - 1.46 MW
- External NASA funded motor development
  - >13 kW/kg
  - >1 MW
  - >96% Efficient
  - Teams at UIUC & OSU
- All teams have chosen Litz wire or form wound conductors to meet their goals
- High power densities = higher temperatures = more loss (10 °C increase in temperature is a 3.9% increase in resistive loss)
Litz Wire

- Litz wire reduces losses due to induced eddy currents
- Parallel conduction of current in the motor-strands at roughly the same potential
  - Standard magnet wire electrical insulation on each strand is a significant over design
- Litz wire offers a unique design space for new material solutions
Inside a Stator Slot

- Slot
  - soft magnetic material

- Wire insulation
  - electric isolation, polyimde \(\sim 0.1 \text{ W/m-K}\)

- HV Insulation
  - electrical isolation, polyamide or mica (1-2W/m-K)

- Potting material
  - mechanical stabilization/thermal management*
  - epoxy \(\sim 2\text{W/m-K}\) (with some exceptions)

Potted AWG 38 (101 micrometer diameter) with a heavy build polyimde insulation
Thermal Effects: Potting Material vs. Wire Insulation

From the law of mixtures

\[ K_{\text{transverse}} = \frac{1}{\frac{\eta_{\text{Cu}}}{K_{\text{Cu}}} + \frac{\eta_{\text{ins}}}{K_{\text{ins}}} + \frac{\eta_{\text{epoxy}}}{K_{\text{epoxy}}}} \]

\[ K_{\text{axial}} = K_{\text{Cu}}\eta_{\text{Cu}} + K_{\text{ins}}\eta_{\text{ins}} + K_{\text{epoxy}}\eta_{\text{epoxy}} \]

- Increasing the thermal conductivity of the potting material (epoxy) has a significant effect on thermal conductivity
- Wire insulation is a significant thermal choke
- Does ins the traditional wire insulation necessary with Litz wire-could it be replaced with the potting material
Finite Element Analysis (FEA) of the High Voltage Insulation

High voltage insulation breakdown (> 2x operating voltage of the motor) is necessary between phases in a stator slot and between the conductor and back iron.

FEA of a theoretical motor slot. High voltage insulation wraps each Litz wire. High voltage insulation thermal conductivity (a) 0.12 W/m-K and (b) 0.24 W/m-K.
Rudimentary Unit Cells (RUC)

RUCs allow for rapid reproduction of common (repeated) structures in a composite material.
High Fidelity Generalized Method of Cells (HFGMC)

Provides a 10x increase in computational speed while minting most of the accuracy of FEA

Makes computations of large number of the repeated structures possible
Preliminary Micro Thermal Modeling Results

Hexagonal
Conductor ~ 55-60%
Insulator ~20%-30%
Potting material~15-20%

\[ \begin{align*}
K_\parallel &= 380 \text{ W/m-K} \\
K_{\perp 22} &= 0.79750 \text{ W/m-K} \\
K_{\perp 33} &= 0.79529 \text{ W/m-K}
\end{align*} \]

Square
<<Place holder for pickling factors>>

\[ \begin{align*}
K_\parallel &= 290 \text{ W/m-K} \\
K_{\perp 22} &= 0.86730 \text{ W/m-K} \\
K_{\perp 33} &= 0.86730 \text{ W/m-K}
\end{align*} \]

Random I and II
Conductor: 45-50%
Insulator: 20%-30%
Potting material: 25-30%

\[ \begin{align*}
K_\parallel &= 240 \text{ W/m-K} \\
K_{\perp 22} &= 0.442 \text{ W/m-K} \\
K_{\perp 33} &= 0.421 \text{ W/m-K}
\end{align*} \]

\[ \begin{align*}
K_\parallel &= 255 \text{ W/m-K} \\
K_{\perp 22} &= 0.528 \text{ W/m-K} \\
K_{\perp 33} &= 0.524 \text{ W/m-K}
\end{align*} \]
Summary & Conclusions

- Conceptualizing the insulation materials systems as composite is the key gaining to multi-functionality
  - Electrical
  - Thermal
  - Mechanical

- Composite approach provides modest, achievable goals can be set. thermal conductivities for
  - potting materials > 1 W/m-K, and
  - High Voltage Insulation ~ 0.5 W-m/K
  - possibly replacing or eliminating the insulation material on the Litz wire. These
  - goals are backed up by finite element modeling.

- Higher fidelity micro thermal modeling along with testing and model validation will bring more clarity to how the physical system behaves and will also refine the material development goals.
Acknowledgments

- Advanced Air Transport Technology Project, Hybrid Gas Electric Propulsion Program – Amy Jankovsky and Cheryl Bowman
- Transformative Tool and Technology Program – Janet Hurst

**Electric Machine Insulation Development Team**
- Tiffany Williams
- Maricela Lizcano
- Daniel Scheiman
- Marisabel Kelly
- Kathy Chuang

**99% Efficient Motor Development Team**
- Yaritza DeJesus - Arcer
- Paul Passe
- Sean McCormick
- Pete Kascak
- Justin Scheidler
- Ryan Edwards
- Erik Stalcup
- Jarred Wilhite
Thank you!